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Design considerations of Step-down Switching Converters

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Abstract

To obtain the design method of inductance and capacitance of a step-down switching converter, its Output Voltage Ripple (OVR) in CCM and DCM is analyzed. The Maximum OVR(MOVR) in each operating region is obtained, respectively. It is pointed out that the minimum inductance to guarantee the lowest OVR is the critical inductance of CCM and DCM under the highest input voltage and heaviest load. The design method of inductance and capacitance is proposed according to the desired OVR level within the total operating range. The analysis and feasibility of the proposed method are verified by the experiment results.

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Keywords: Switching converter; Voltage ripple; Design

1. Introduction

Because of its small size and high efficiency, the switching power supply will be competitive in the future in flammable and explosive conditions[1]. With the development of science and technology, the working voltage of electronic apparatus becomes lower and lower. Therefore, Step-down switching converters will be widely used in the related fields[2-4]. However, there are some energy-storage elements in the converters, such as inductors and the capacitors, which will produce sparks when a capacitor is short-circuit or an inductor is disconnected. Those sparks may ignite the prescriptive gases or their mixtures. Thus, the key to design an switching converter used in flammable and explosive conditions is to manage the capacitance and inductance as small as possible but still meet the requirements of the electric performance [5], such as the OVR [6]. In this paper, the OVR of a Step-down converter is analyzed within the given range of the input voltage and load resistance. The relationship between the OVR and the element parameters of the converter is deduced, and the minimum inductance to guarantee the OVR to be the lowest is obtained, which plays an important role in the optimal design of compact Step-down converters.

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2. Operating region and critical inductance

A Step-down converter is shown in Fig.1. If it operates in CCM, the relationship between the input voltage (V_i) and output voltage (V_o) is $d=V_o/V_i$, where d is the conducting ratio and $d=T_{on}/T_s$, T_s is switching period and T_{on} is conducting time of the switch. Critical inductance L_C of CCM and DCM is [7]

$$L_C = \frac{R_L(V_i - V_o)}{2f\ V_i} \tag{1}$$

Where R_L is the load resistance, f is the switching frequency. Supposing that the input voltage range of the converter is from $V_{i,min}$ to $V_{i,max}$ and the load range is from $R_{L,min}$ to $R_{L,max}$, the operating region of the converter is a rectangle in R_L-V_i plane, which is shown in Fig.2. According to (1), the corresponding curves of various L_C can be drawn in Fig.2. According to (1), the critical inductance of CCM and DCM corresponding to point A, B and C are given by (2).

$$L_{CA} = \frac{R_{L,min}(V_{i,min} - V_o)}{2fV_{i,min}}\ ,\quad L_{CB} = \frac{R_{L,min}(V_{i,max} - V_o)}{2fV_{i,max}}\ ,\quad L_{CC} = \frac{R_{L,max}(V_{i,max} - V_o)}{2fV_{i,max}} \tag{2}$$

From Fig.2, we can see that the converter operates in CCM in the case of $L>L_{CC}$ within the whole operating range, corresponding to the curve of L_{C1}, while in DCM in the case of $L<L_{CA}$, corresponding to the curve of L_{C4}. When $L_{CA}<L<L_{CC}$, it may be in CCM or DCM, corresponding to the curve of L_{C2} or L_{C3}.

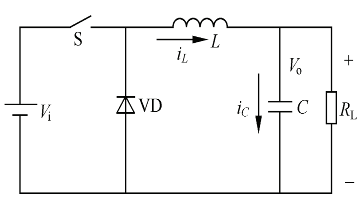

Fig. 1. A typical Step-down switching converter

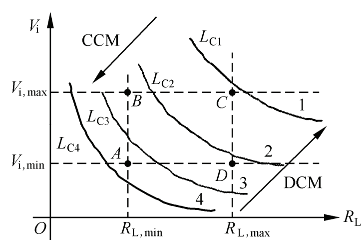

Fig. 2. CCM and DCM region in R_L-V_i plane

3. OVR of a step-down converter

The OVR of Step-down converter in CCM [7] is

$$V_{PP,CCM} = \frac{V_o(V_i - V_o)}{8LCf^2V_i} = \frac{V_o(1 - V_o/V_i)}{8LCf^2} \tag{3}$$

Obviously, $V_{PP,CCM}$ is independent of the load resistance and increases with the increase of V_i. The OVR $V_{PP,DCM}$ of Step-down converter in DCM [7] is

$$V_{PP,\ DCM} = \frac{V_o}{fCR_L} + \frac{LV_oV_i}{2CR_L^2(V_i - V_o)} - \frac{V_o}{fC}\sqrt{\frac{2LfV_i}{R_L^3(V_i - V_o)}} \tag{4}$$

Taking the partial derivatives with respect to R_L and V_i on (4), respectively, we can obtain

$$\frac{\partial(V_{PP,DCM})}{\partial R_L} < 0\ ,\ \frac{\partial(V_{PP,DCM})}{\partial V_i} > 0 \tag{5}$$

4. The maximum OVE of a step-down converter

According to the inductance, the operating region can be divided into four parts within the whole operating range. The MOVR of each part is analyzed as follows.

A. For $L>L_{CC}$

When $L>L_{CC}$, it is in CCM within the whole operating range. According to (3), the MOVR $V_{PP1,\ max}$ is

$$V_{PP1,\ max} = \frac{V_o(V_{i,\ max} - V_o)}{8LCf^2 V_{i,\ max}} \tag{6}$$

Obviousely, $V_{PP1,\ max}$ increases with the decrease of L and reaches the largest value in the case of L=L_{CC}. Moreover, according to (2) and (6), we can obtain that the maximum value of $V_{PP1,\ max}$ is

$$\max\{V_{PP1,\ max}\} = \frac{V_o}{4fCR_{L,\ max}} \tag{7}$$

Obviously, the maximum value of $V_{PP1,max}$ decreases with the increase of $R_{L,max}$.

B. For L<L

B. *For $L<L_{CA}$*

When $L<L_{CA}$, the converter operates in DCM within the whole operating range. According to (4) and (5), the OVR in this case reaches the maximum value $V_{PP4,max}$ in the case of V_i=$V_{i,max}$ and R_L=$R_{L,min}$. Moreover, $V_{PP4,max}$ is given by

$$V_{PP4,\ max} = \frac{V_o}{fCR_{L,\ min}} + \frac{LV_oV_{i,\ max}}{2CR_{L,\ min}^2(V_{i,\ max} - V_o)} - \frac{V_o}{fC}\sqrt{\frac{2LfV_{i,\ max}}{R_{L,\ min}^3(V_{i,\ max} - V_o)}} \tag{8}$$

Because of $\frac{\partial(V_{PP4,max})}{\partial L} < 0$, $V_{PP4,max}$ increases with the decrease of L.

C. *For $L_{CA}<L<L_{CC}$*

For $L_{CA}<L<L_{CC}$, it can be divided into two case, i.e., $L_{CA}<L<L_{CB}$ and $L_{CB}<L<L_{CC}$.

- $L_{CA}<L<L_{CB}$

In this case, the Step-down converter operates in DCM in its larger operating region, corresponding to the curve of L_{C3} which is shown in Fig.3. The critical inductance L_{CE} corresponding to point E is

$$L = L_{CE} = \frac{R_{L,\ min}(V_{iE} - V_o)}{2fV_{iE}} \tag{9}$$

V_{iE} is the input voltage corresponding to point E. From Fig.3, we can see that piont B is in DCM region.

It is in DCM in the region enclosed by BCDFE, thus, the MOVR $V_{PP3,\ max}^{(DCM)}$ in this case is

$$V_{PP3,\ max}^{(DCM)} = \frac{V_o}{fCR_{L,\ min}} + \frac{LV_oV_{i,\ max}}{2CR_{L,\ min}^2(V_{i,\ max} - V_o)} - \frac{V_o}{fC}\sqrt{\frac{2LfV_{i,\ max}}{R_{L,\ min}^3(V_{i,\ max} - V_o)}} \tag{10}$$

Because of $\frac{\partial V_{PP3,\ max}^{(DCM)}}{\partial L} < 0$, $V_{PP3,\ max}^{(DCM)}$ decreases with the increase of L and reaches the minimum value in the case of L=L_{CB}, moreover, its minimum value is

$$\min\{V_{PP3,\ max}^{(DCM)}\} = \frac{V_o}{4fCR_{L,\ min}} \tag{11}$$

When the converter operates in the region enclosed by AEF, it operates in CCM, $V_{PP3,\ max}^{(CCM)}$ is

$$V_{PP3,\ max}^{(CCM)} = \frac{V_o(V_{iE} - V_o)}{8LCf^2V_{iE}} \tag{12}$$

From (9) - (12), we can obtain

$$\max\{V_{PP3,\ max}^{(CCM)}\} = \frac{V_o}{4fCR_{L,\ min}}, \quad V_{PP3,\ max}^{(DCM)} \ge V_{PP3,\ max}^{(CCM)} \tag{13}$$

Therefore, considering (10), the MOVR $V_{PP3,max}$ in the case of $L_{CA}<L<L_{CB}$ is given by

$$V_{PP3,\ max} = V_{PP3,\ max}^{(DCM)} = \frac{V_o}{fCR_{L,\ min}} + \frac{LV_oV_{i,\ max}}{2CR_{L,\ min}^2(V_{i,\ max} - V_o)} - \frac{V_o}{fC}\sqrt{\frac{2LfV_{i,\ max}}{R_{L,\ min}^3(V_{i,\ max} - V_o)}} \tag{14}$$

Because $V_{PP3,\ max}$ increases with the decrease of L, its maximum value can be obtained in the case of L=L_{CA}, considering (2), we can deduce

$$\max\left\{V_{\text{PP3, max}}\right\} = \frac{V_o}{4fCR_{\text{L, min}}}\left(2 - \sqrt{\frac{1 - V_o/V_{\text{i, min}}}{1 - V_o/V_{\text{i, max}}}}\right)^2 \tag{15}$$

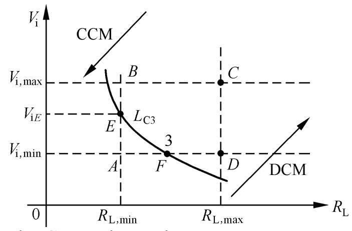

Fig. 3. CCM and DCM regions when $L_{CA}<L<L_{CB}$

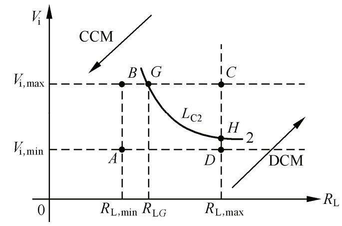

Fig. 4. CCM and DCM regions when $L_{CB}<L<L_{CC}$

- $L_{CB}<L<L_{CC}$

In this case, the Step-down converter is in CCM in its larger operating region, corresponding to the curve of L_{C2} which is shown in Fig.4. The critical inductance L_{CG} corresponding to point G is

$$L = L_{CG} = \frac{R_{LG}(V_{\text{i, max}} - V_o)}{2fV_{\text{i, max}}} \tag{16}$$

R_{LG} is the load resistance corresponding to point G. From Fig.4, we can see that piont B is in CCM region. Applying the similar analyzing methods mentioned above, we have

$$V_{\text{PP2,max}}^{(\text{CCM})} = \frac{V_o\left(V_{\text{i,max}} - V_o\right)}{8LCf^2V_{\text{i,max}}}, \quad \min\left\{V_{\text{PP2, max}}^{(\text{CCM})}\right\} = \frac{V_o}{4fCR_{LG}} \tag{17}$$

$$V_{\text{PP2,max}}^{(\text{DCM})} = \frac{V_o}{fCR_{LG}} + \frac{LV_oV_{\text{i,max}}}{2CR_{LG}^2\left(V_{\text{i,max}} - V_o\right)} - \frac{V_o}{fC}\sqrt{\frac{2LfV_{\text{i,max}}}{R_{LG}^3\left(V_{\text{i,max}} - V_o\right)}}, \quad \max\left\{V_{\text{PP2, max}}^{(\text{DCM})}\right\} = \frac{V_o}{4fCR_{LG}} \tag{18}$$

Comparing (17) and (18), we have

$$V_{\text{PP2, max}}^{(\text{CCM})} \ge V_{\text{PP2, max}}^{(\text{DCM})} \tag{19}$$

Because $V_{\text{PP2, max}}^{(\text{CCM})}$ decreases with the increase of L, the maximum value of the $V_{\text{PP2, max}}^{(\text{CCM})}$ can be obtained in the case of $L=L_{CB}$. Considering (2) and (17), we can deduce

$$\max\left\{V_{\text{PP2, max}}^{(\text{CCM})}\right\} = \frac{V_o}{4fCR_{\text{L,min}}} \tag{20}$$

Because of $R_{LG}>R_{\text{L, min}}$, considering (11), (13), (17), (18), (19) and (20), we can obtain

$$V_{\text{PP3, max}}^{(\text{DCM})} \ge V_{\text{PP3, max}}^{(\text{CCM})} \ge V_{\text{PP2, max}}^{(\text{CCM})} \ge V_{\text{PP2, max}}^{(\text{DCM})} \tag{21}$$

To meet the requirements of the miniaturization, the inductance should be designed in the range of $L_{CA}<L<L_{CC}$, therefore, the MOVR of the converter in the whole operating range can be obtained in the case of $V_i=V_{\text{i,max}}$ and $R_L=R_{\text{L,min}}$. Considering (10) and (21), the MOVR is

$$V_{\text{PP, max}} = V_{\text{PP3, max}}^{(\text{DCM})} = \frac{V_o}{fCR_{\text{L, min}}} + \frac{LV_oV_{\text{i, max}}}{2CR_{\text{L, min}}^2(V_{\text{i, max}} - V_o)} - \frac{V_o}{fC}\sqrt{\frac{2LfV_{\text{i, max}}}{R_{\text{L, min}}^3(V_{\text{i, max}} - V_o)}} \tag{22}$$

5. Design considerations

On the one hand, for a switching converter, the operating mode of DCM is suggested to be avoided when the load is heavy, because the peak current in DCM is higher than that in CCM with the same power level and the current stress on the power switch is also higher. Thus, the inductance should meet the condition of $L>L_{CB}$. On the other hand, if the converter is in CCM within the whole operating range, the OVR is the lowest as mentioned above and the current stress on the switch is small. But according to (2), the inductance must satisfy

$$L > L_{CC} = \frac{R_{\text{L,max}}(V_{\text{i,max}} - V_o)}{2fV_{\text{i,max}}} \tag{23}$$

Obviously, the inductance is very large in the case of rather large $R_{L,\max}$ and it is difficult to meet the requirements of the miniaturization. Therefore, it is not desired for the converter to be in CCM in the whole operating range. So the inductance should be less than L_{CC}, that is $L<L_{CC}$. Thus, the design range of the inductance is $L_{CB}<L<L_{CC}$, considering (17) and (21), the maximum value of the OVR is given by

$$V_{\mathrm{PP,max}} = V_{\mathrm{PP2,max}}^{\mathrm{CCM}} = \frac{V_{\mathrm{o}}\left(1-V_{\mathrm{o}}/V_{\mathrm{i,max}}\right)}{8LCf^2} \tag{24}$$

To meet the requirements of the miniaturization, the optimal design is to select an inductance as small as possible to guarantee the MOVR to be the lowest one in the whole operating range. According to (11) and (22), the MOVR is the lowest in the case of $L=L_{CB}$. Therefore, the minimum inductance is given by

$$L_{\min} = L_{\mathrm{CB}} = \frac{R_{\mathrm{L,min}}(V_{\mathrm{i,max}} - V_{\mathrm{o}})}{2fV_{\mathrm{i,max}}} \tag{25}$$

Considering (24), the minimum capacitance is

$$C'_{\min} = \frac{1-V_{\mathrm{o}}/V_{\mathrm{i,max}}}{8Lf^2m} \tag{26}$$

Where $m=V_{\mathrm{PP,max}}/V_{\mathrm{o}}$. Because of the ESR and ESL of the capacitor, we may introduce an multiple factor λ in designing the capacitance to reach the desired voltage ripple level, i.e.

$$C_{\min} = \lambda C'_{\min} = \frac{\lambda\left(1-V_{\mathrm{o}}/V_{\mathrm{i,max}}\right)}{8Lf^2m} \quad (\lambda=1.5\sim3) \tag{27}$$

6. Examples and verification

6.1. The design of inductance and capacitance

To verify the above theory, the parameters of the designed converter are as follows: V_{i} =21~27V, V_{o}=18V, $V_{\mathrm{PP,max}}$=2%V_{o}, R_{L}=36Ω~180Ω, f=52kHz. According to the above analysis, we can obtain L_{CA}=49μH, L_{CB}=115μH, L_{CC}=577μH, thus, $L_{\min}$=115μH. According to (27) and considering $V_{\mathrm{PP,\,max}}$=2%V_{o}, we can obtain that the minimum value of the capacitance is $C_{\min}$=10μF (λ=1.5).

6.2. The analysis of the experiment results

In order to verify above theory, the following experiments (where C is 10μF) are done.

i). When the load resistance is in the range of 36~180Ω, change the input voltage from 21V to 27V and let L=90μH, L=130μH, respectively. The experiment curves of V_{PP} are shown in Fig.5.

From Fig.5, we can see that OVR in CCM is independent of R_{L}, but decreases with increase of R_{L} in DCM. OVR in both CCM and DCM increases with the increase of V_{i}. OVR in the case of L=90μH is larger than that in the case of L=130μH within given range of R_{L} and V_{i}. The maximum OVR is 0.38V in the case of $V_{\mathrm{i}}=V_{\mathrm{i,max}}$ and $R_{\mathrm{L}}=R_{\mathrm{L,min}}$. Obviously, if $L_{\mathrm{CA}}<L<L_{\mathrm{CB}}$, the converter with the heaviest load operates in CCM in the case of $V_{\mathrm{i}}=V_{\mathrm{i,min}}$ and in DCM in the case of $V_{\mathrm{i}}=V_{\mathrm{i,max}}$. Furthermore, OVR reaches the largest value in the case of $V_{\mathrm{i}}=V_{\mathrm{i,max}}$. Therefore, to obtain smaller OVR, the inductance should be designed in the range of $L_{\mathrm{CB}}<L<L_{\mathrm{CC}}$.

ii). When R_{L} is the minimum ($R_{\mathrm{L}}=R_{\mathrm{L,min}}$=36Ω) and the inductor is evaluated in the range of $L_{\mathrm{CA}}<L<L_{\mathrm{CB}}$, the relationship between V_{PP}, V_{i} and L is shown in Fig.6.

From Fig.6, we can see that OVR decreses with the increse of the inductance and increases with the increase of V_{i}. OVR reaches the maximum value in the case of $V_{\mathrm{i}}=V_{\mathrm{i,max}}$=27V and the MOVR reaches the minimum value in the case of $L=L_{\mathrm{CB}}$=115μH. It is obvious that the minimum inductance to guarantee the lowest OVR is the critical inductance of CCM and DCM under the highest input voltage and the heaviest load. From Fig.5 and Fig.6, we can see that the MOVR must be less than 2%V_{o}=0.36V when the inductance is designed in range of $L_{\mathrm{CB}}<L<L_{\mathrm{CC}}$, otherwise, the MOVR may be larger than 0.36V. Obviously, the designed Step-down converter achieves the desired goals, the feasibility of the theoretical analysis and design method is verified by the experiment results.

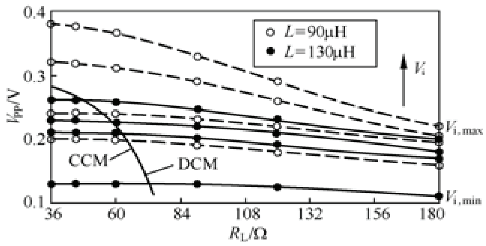

Fig. 5. Relationship between V_{PP}, V_i and R_L

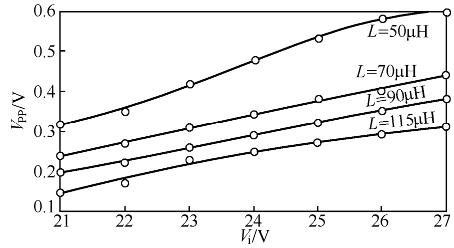

Fig. 6. Relationship between V_{PP}, V_i and L

7. Conclusions

The OVR is independent of the load resistance for the CCM Step-down converters and decreases with increase of the load resistance for the DCM Step-down converters. The minimum inductance to guarantee the lowest OVR is the critical inductance of CCM and DCM under the highest input voltage and the heaviest load. According to the desired OVR level within the total operating range, the design considerations of inductance and capacitance of Step-down switching converter are proposed. The design methods are very significant for designing the desired Step-down switching converters.

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